Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 1 (SH), pages 733–736

30TH INTERNATIONAL COSMIC RAY CONFERENCE

World Grid of Calculated Cosmic Ray Vertical Cutoff Rigidities for Epoch 1995.0

D.F. SMART[1], M.A. SHEA[1]
[1]*Air Force Research Laboratory, (VSBX), 29 Randolph Road, Hanscom AFB, Bedford, MA 01731,* USA.
sssrc@msn.com

Abstract: A world grid of vertical cosmic ray cutoff rigidities was calculated using the Definitive International Geomagnetic Reference Field for Epoch 1995.0. These cutoff rigidity values show the effects of the continued evolution of the geomagnetic field. The average cutoff values continue to decrease especially in the South Atlantic and South American areas. However, in some areas of the world, the cutoff values are increasing. These cutoff rigidity values have extensive use, especially for computing aircraft radiation dose by the CARI-6 software.

Introduction

We have continued to determine cosmic-ray cutoff rigidities by the trajectory-tracing method whereby the orbit of a particle of specified rigidity is traced, by numerical methods, through a model of the geomagnetic field to determine if the particle is allowed or forbidden for a specific zenith and azimuth at a given location. We have derived a world grid of vertically incident cosmic ray cutoff rigidities employing the Definitive International Geomagnetic Reference Field [1] for Epoch 1995 (DGRF95). Geomagnetic cutoff rigidities were calculated each 5° in latitude and 5° in longitude so that a comparison can be made between these values and the values calculated for previous epochs [2-7].

Method

The cosmic ray trajectory calculations were initiated in the "vertical" direction at an altitude of 20 km above the surface of the international reference ellipsoid. The "sensible" atmosphere of the earth was considered to be 20 km, and any trajectory path that comes lower than this distance was assumed to be re-entrant and hence forbidden. In this work "vertical" is the direction normal to the surface of the international reference ellipsoid. Our standard cosmic ray trajectory-tracing technique was used employing the step size criteria where the length of each iteration step is about 1% of a gyro-distance (the distance the particle of the specified rigidity would travel during one gyration in a uniform magnetic field of the same intensity). The cutoff rigidities are determined by calculating cosmic ray trajectories at discrete rigidity intervals starting with a rigidity value high above the highest possible cutoff and decreasing the rigidity to a value that satisfied our criteria that the lowest allowed trajectory had been calculated. As these calculations progress down through the rigidity spectrum, the results change from the easily allowed orbits to a complex structure of allowed, forbidden, and quasi-trapped orbits (loosely called penumbra) and finally to a set of rigidities where all trajectories intersect the solid earth. As a result of these trajectory calculations we determined the calculated upper cutoff rigidity (R_U) which is the rigidity value of the highest allowed/forbidden pair of adjacent cosmic ray trajectories, and the calculated lower cutoff rigidity (R_L) which is the rigidity value of the lowest allowed/forbidden pair of adjacent cosmic ray trajectories. We also determine an "effective cutoff rigidity" (R_C) by summing over the allowed orbits in the penumbra. (See [8] for an updated definition of cosmic ray cutoffs, and [9] for a detailed definition of R_C.) Rigidity intervals of 0.01 GV were used for trajectories between R_U and R_L to provide a reasonable sample of the cosmic ray penumbra.

Results and Discussion

These results are intended to be a reference for evaluating the effects attributable to the quiescent internal geomagnetic field. These cutoff rigidity values have extensive use, especially for computing aircraft radiation dose by the CARI-6 software [10]. A reduced (for the lack of space) 5° in latitude by 15° in longitude tabulation is given in Table 1. When these values are compared with those calculated for previous epochs, significant differences are noted [11]. Decreases in vertical cutoff rigidity were found for many grid points in the eastern part of the Pacific Ocean area, over South America, and the South Atlantic ocean. The cutoffs in the South Atlantic region are decreasing at a rate of the order of 0.5% per year over a wide area. The largest systematic decreases, of the order of 1.5 GV over the last 40 years are in the South Atlantic Ocean area around 30° S, 320° E. However, there are some areas where the vertical cutoff rigidities are increasing. The magnitude of this change is 1 GV or greater in the North Atlantic Ocean area over the last 40 years. The largest systematic increases are distributed through the mid-Atlantic Ocean from the Caribbean to Europe. A maximum increase occurs at a position of 30° N, 315° E.

Conclusions

Vertical cutoff rigidities for Epoch 1995.0 continue to show significant and systematic changes from the previous epochs. There is an "average" decrease reflecting the changes in the main dipole component; however, these changes are not uniform over the world, suggesting the non-dipole terms are relatively important for an accurate determination of cutoff rigidities near the surface of the earth. With modern high speed computers it is now possible to calculate specific cutoff rigidity values utilizing the updated International Geomagnetic Reference Field (IGRF) models for a specific epoch.

Acknowledgments

These calculations were performed at the Maui High Performance Computer Center.

References

[1] T.J. Sabaka, et al., The geomagnetic field, 1900-1995, Including the large scale fields from magnetospheric sources and NASA candidate models for the IGRF 1995 revision, J. Geomag. Geoelectr., 49, 157-206, 1997.

[2] M.A. Shea, D.F. Smart, J.R. McCall, A five degree by fifteen degree world grid of trajectory-determined vertical cutoff rigidities, Can. J. Phys., 46, s1098, 1968.

[3] M.A. Shea, D.F. Smart, Tables of asymptotic directions and vertical cutoff rigidities as calculated using the international geomagnetic reference field for epoch 1975.0, AFCRL TR-75-0185, 1975.

[4] M.A. Shea, D.F. Smart, Tables of asymptotic directions and vertical cutoff rigidities as calculated using the international geomagnetic reference field for epoch 1965.0, AFCRL TR-75-0381, 1975.

[5] M.A. Shea, D.F. Smart, A five by fifteen degree world grid of calculated cosmic-ray vertical cutoff rigidities for 1965 and 1975, 14th ICRC, 4, 1298-1293, 1975.

[6] M.A. Shea, D.F. Smart, A world grid of calculated cosmic ray vertical cutoff rigidities for 1980.0, 18th ICRC, 3, 415-418, 1983.

[7] M.A. Shea, D.F. Smart, A world grid of calculated cosmic ray vertical cutoff rigidities for 1990.0, 25th ICRC, 2, 401-404, 1997

[8] D.J. Cooke, et al., On cosmic-ray cut-off terminology, Il Nuovo Cimento C, 14, 213-234, 1991.

[9] M.A. Shea, D.F. Smart, K.G. McCracken, A study of vertical cutoff rigidities using sixth degree simulations of the geomagnetic field, J. Geophys. Res., 70, 4117-4130, 1965.

[10] CARI-6 http://www.cami.jccbi.gov/AAM-600/610/600Radio.html

[11] M.A. Shea, D.F. Smart, Secular changes in the geomagnetic cutoff rigidities and the effect on cosmic ray measurements, 25th ICRC, 2, 393-396, 1997.

Table 1. Vertical Effective Cutoff Rigidities (in GV) for Epoch 1995.0

Geographic East Longitude

Lat	0	15	30	45	60	75	90	105	120	135	150	165
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
85	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01
80	0.02	0.04	0.05	0.06	0.06	0.07	0.07	0.08	0.08	0.07	0.07	0.06
75	0.08	0.13	0.15	0.17	0.19	0.18	0.21	0.23	0.21	0.22	0.22	0.20
70	0.24	0.32	0.38	0.41	0.43	0.43	0.46	0.48	0.51	0.54	0.52	0.51
65	0.59	0.68	0.74	0.83	0.84	0.87	0.91	0.97	1.01	1.10	1.12	1.07
60	1.10	1.28	1.40	1.45	1.53	1.61	1.61	1.72	1.82	1.94	1.99	1.91
55	2.01	2.25	2.35	2.39	2.49	2.59	2.71	2.79	2.98	3.19	3.18	3.06
50	3.30	3.53	3.69	3.74	3.94	3.98	4.18	4.32	4.53	4.90	4.76	4.53
45	4.91	5.13	5.23	5.29	5.47	5.71	5.88	6.06	6.41	6.70	6.70	6.28
40	7.13	7.35	7.36	7.44	7.78	8.23	8.65	8.92	9.36	9.77	9.61	8.80
35	9.76	9.74	9.95	10.27	10.74	11.28	11.22	11.41	11.74	11.99	11.50	10.50
30	11.61	11.76	11.93	12.33	12.82	13.53	14.00	14.16	14.12	13.87	13.36	12.63
25	13.29	13.64	13.94	14.26	14.72	15.22	15.54	15.59	15.40	14.99	14.37	13.64
20	14.19	14.58	14.91	15.28	15.78	16.31	16.62	16.61	16.32	15.80	15.13	14.43
15	14.62	15.06	15.45	15.89	16.44	16.99	17.29	17.25	16.90	16.33	15.67	15.03
10	14.64	15.12	15.58	16.08	16.70	17.26	17.57	17.52	17.16	16.60	16.00	15.45
5	14.30	14.78	15.29	15.88	16.55	17.13	17.46	17.43	17.10	16.59	16.08	15.66
0	13.62	14.09	14.64	15.30	16.02	16.62	16.96	16.98	16.70	16.29	15.91	15.63
-5	12.70	13.10	13.67	14.39	15.15	15.75	16.10	16.17	15.97	15.66	15.44	15.32
-10	11.56	11.91	12.48	13.23	13.98	14.53	14.86	14.98	14.87	14.67	14.60	14.67
-15	10.13	10.47	11.03	11.78	12.43	12.96	13.21	13.33	13.25	13.23	13.33	13.60
-20	8.52	8.75	9.20	9.83	10.33	10.65	10.73	10.80	10.84	10.54	10.66	11.84
-25	7.07	7.23	7.59	7.99	8.12	7.82	7.42	7.38	7.40	7.65	8.40	9.48
-30	5.78	5.72	5.83	5.87	5.71	5.37	5.23	5.16	5.09	5.37	5.82	6.54
-35	4.72	4.33	4.33	4.34	4.18	3.94	3.49	3.36	3.37	3.57	4.11	4.90
-40	3.85	3.52	3.47	3.27	2.89	2.57	2.18	2.06	2.03	2.22	2.58	3.18
-45	3.16	2.78	2.54	2.29	1.92	1.56	1.28	1.10	1.10	1.20	1.47	2.07
-50	2.55	2.16	1.90	1.61	1.31	0.93	0.68	0.53	0.51	0.60	0.75	1.09
-55	2.00	1.68	1.42	1.10	0.81	0.53	0.33	0.23	0.22	0.24	0.36	0.55
-60	1.51	1.21	0.96	0.74	0.50	0.28	0.13	0.07	0.05	0.07	0.12	0.25
-65	1.19	0.90	0.66	0.47	0.27	0.14	0.05	0.02	0.01	0.01	0.03	0.09
-70	0.79	0.61	0.43	0.29	0.15	0.06	0.02	0.00	0.00	0.00	0.01	0.03
-75	0.53	0.38	0.25	0.16	0.08	0.04	0.01	0.00	0.00	0.00	0.00	0.01
-80	0.30	0.24	0.15	0.10	0.06	0.03	0.01	0.00	0.00	0.00	0.00	0.01
-85	0.16	0.13	0.10	0.07	0.05	0.04	0.03	0.02	0.02	0.02	0.02	0.03
-90	0.07	0.06	0.07	0.07	0.07	0.06	0.07	0.06	0.07	0.07	0.06	0.07

Table 1, (Continued). Vertical Effective Cutoff Rigidities (in GV) for Epoch 1995.0

Geographic East Longitude

Lat	180	195	210	225	240	255	270	285	300	315	330	345
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
85	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80	0.05	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
75	0.17	0.11	0.06	0.03	0.01	0.00	0.00	0.00	0.00	0.01	0.03	0.06
70	0.42	0.33	0.19	0.10	0.05	0.02	0.01	0.01	0.03	0.05	0.10	0.16
65	0.91	0.73	0.49	0.30	0.16	0.08	0.05	0.06	0.09	0.18	0.30	0.47
60	1.69	1.32	0.93	0.64	0.38	0.22	0.17	0.17	0.25	0.44	0.68	0.94
55	2.74	2.20	1.68	1.21	0.80	0.50	0.38	0.42	0.58	0.91	1.32	1.79
50	4.18	3.43	2.75	2.07	1.44	1.01	0.78	0.80	1.08	1.62	2.32	2.93
45	5.44	4.83	4.09	3.13	2.38	1.72	1.38	1.38	1.89	2.65	3.79	4.51
40	7.73	6.43	5.43	4.64	3.56	2.74	2.20	2.18	2.85	4.14	5.37	6.38
35	9.43	8.91	7.67	6.03	5.06	4.05	3.21	3.21	4.15	5.68	8.12	9.37
30	11.59	10.42	9.66	8.66	6.78	5.36	4.33	4.28	5.58	8.57	10.55	11.18
25	12.91	12.26	11.59	10.71	9.37	7.43	5.93	5.83	7.98	10.73	12.09	12.85
20	13.76	13.19	12.67	12.00	10.98	8.87	7.41	7.05	9.56	12.06	13.06	13.72
15	14.44	13.93	13.48	12.96	12.10	10.54	8.99	9.25	11.60	12.79	13.59	14.15
10	14.95	14.50	14.10	13.65	12.99	12.03	11.10	11.33	12.36	13.18	13.77	14.20
5	15.27	14.89	14.51	14.11	13.61	12.91	12.26	12.26	12.74	13.30	13.64	13.91
0	15.37	15.05	14.71	14.34	13.92	13.40	12.87	12.65	12.88	13.17	13.26	13.34
-5	15.19	14.97	14.69	14.37	14.00	13.57	13.08	12.78	12.80	12.85	12.69	12.55
-10	14.72	14.62	14.43	14.19	13.89	13.52	13.08	12.71	12.55	12.36	11.92	11.52
-15	13.87	13.97	13.93	13.81	13.60	13.30	12.89	12.46	12.14	11.73	11.05	10.26
-20	12.57	12.96	13.16	13.21	13.13	12.91	12.54	12.07	11.59	10.88	9.87	8.93
-25	9.99	11.02	11.84	12.39	12.49	12.38	12.06	11.55	10.88	9.93	8.68	7.58
-30	7.90	9.30	9.05	10.75	11.63	11.70	11.46	10.87	9.98	8.90	7.37	6.54
-35	5.55	6.50	7.87	8.25	9.87	10.85	10.73	10.07	9.11	7.70	6.38	5.45
-40	4.11	4.66	5.52	6.69	8.15	9.69	9.67	9.14	8.09	6.60	5.73	4.52
-45	2.62	3.33	4.22	4.89	6.06	7.74	8.64	8.10	7.34	6.23	4.69	3.77
-50	1.66	2.21	2.91	3.75	4.58	5.47	6.78	6.90	6.08	4.80	3.90	3.11
-55	0.90	1.36	1.91	2.62	3.35	4.18	4.76	4.81	4.50	3.88	3.16	2.45
-60	0.46	0.78	1.19	1.73	2.28	2.97	3.58	3.74	3.49	3.07	2.43	1.97
-65	0.20	0.42	0.65	1.04	1.50	1.94	2.41	2.53	2.39	2.20	1.87	1.47
-70	0.08	0.21	0.38	0.60	0.91	1.21	1.48	1.61	1.63	1.47	1.24	1.03
-75	0.04	0.10	0.20	0.34	0.51	0.65	0.81	0.93	0.95	0.87	0.80	0.66
-80	0.03	0.06	0.11	0.18	0.25	0.34	0.42	0.47	0.48	0.46	0.46	0.36
-85	0.04	0.05	0.08	0.10	0.12	0.17	0.21	0.19	0.23	0.22	0.19	0.19
-90	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.06